embryological data also give direct evidence for an inference from the phylogeny — that the shell-free state of Aplacophora is the result of character loss; and finally the fossils and the embryology agree on the likely presence of seven shells in the ancestry of the Aplacophora.

There has long been a desire to reconstruct the ancestor of all molluscs — the famous Hypothetical Ancestral Mollusc [1] — and there are intriguing hints that repeated transverse structures might also exist in the other major branch of molluscs, the Conchifera (gastropods, cephalopods, bivalves, monoplacophorans and scaphopods). As in adult polyplacophorans, eight dorsoventral muscles are also found in the Monoplacophora (famous as 'living fossils') and these have further been homologised to eight muscle scars found in the fossilized shells of early bivalves [11].

It is tempting to speculate from these observations that the mollusc ancestors were segmented and to draw comparisons with their lophotrochozoan relatives, the segmented annelid worms. The simultaneous formation of serial muscles in Polyplacophora and Aplacophora, however, differs in an important manner from the sequential addition of segments from anterior to posterior in annelids [5]. And the serial commissures of the polyplacophoran nervous system actually differentiate first at the posterior, suggesting very different underlying ontogenetic mechanisms underlying the body divisions of the two phyla [12].

Interestingly, a very similar approach combining phylogenetics and embryology has shown that, just as the shells typical of molluscs have been lost in the Aplacophora, the segmentation so typical of annelids has been lost in certain annelid sub-groups. Phylogenetic analyses show two groups of unsegmented marine worms, the Echiura and Sipunculida, to be members of the segmented annelids. Parallel studies of their embryology have revealed early ontogenetic stages with a clearly segmented nervous system later lost in the developing adult [13,14]. Each of these studies represent a wonderful use of Haeckelian ontogenetic recapitulation both to reveal hidden phylogenetic affinities and as evidence to resurrect the spirits of long dead ancestors.

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Department of Genetics, Evolution and Environment, University College London, Gower Street, London WC1E 6BT, UK.
E-mail: m.telford@ucl.ac.uk

http://dx.doi.org/10.1016/j.cub.2013.09.045

Brain Biology: Jerked Around by Sleep

During rapid eye movement sleep, the forelimb muscles of newborn rats jerk and twitch in an organized pattern, the fidelity of which improves with time. The coordinated nature of such sleep movements may instruct the developing brain how to more effectively execute movements during wakefulness.

Jimmy J. Fraigne[1] and John H. Peever[1,2,*]

One of the most common misconceptions about rapid eye movement (REM) sleep — called active sleep in newborns — is that it is a time when the body's muscles lie dormant [1]. Many pet owners will have noticed that their sleeping dog or cat can 'act out their dreams', often making gestures as if chasing a rabbit or a mouse. These seemingly bizarre, but normal, behaviors are the result of the muscle jerks and twitches that occur during natural REM sleep [2,3]. For years, many scientists thought these movements to be mere artefacts of the dreaming brain, representing a random succession of movements *without purpose* [4,5]. In this issue of *Current Biology*, however, Blumberg *et al.* [6] contradict this popular notion by showing that REM sleep jerks follow a well-defined and well-organized pattern of movement. This intriguing new finding suggests that the brain plans and coordinates movements during sleep, raising the enticing possibility that such movements are biologically meaningful and may facilitate structured movements during wakefulness.

As most newborn mammals spend the majority of their time in REM sleep, it is believed that this sleep state functions to guide brain maturation during development [7–9]. But it

remains unclear exactly how REM sleep and its associated phenomena (such as muscle twitches) actually foster the developing brain. One possibility is that the sensory signals produced by REM sleep twitches act to drive somatosensory system development [9–11]. Indeed, a recent study [12] found that the barrel cortex and thalamus of newborn rats preferentially respond to whisker movements during REM sleep, suggesting that REM sleep movements contribute to sensorimotor integration. If REM sleep movements do in fact facilitate brain development, then it makes reasonable sense that they would behave in an organized manner, thereby providing temporally structured feedback to guide sensorimotor development. But this idea contradicts the popular belief that REM sleep twitches are nothing more than meaningless motor artefacts [4,5].

Blumberg *et al.* [6] set out on a challenging quest to dispel the myth that sleep movements are random by-products of the dreaming brain. They did this by carefully watching and recording the intricate REM sleep movements of the forelimb muscles and joints in newborn rats. They first noticed that during active (REM) sleep, rat pups experienced rapid twitch activity that appeared to be organized in recognizable bursts interrupted by irregular periods of motor quiescence. The speed and subtlety with which these twitches occurred, however, made it difficult for Blumberg *et al.* [6] to determine if there was a clear relationship between movements of various forelimb structures (the shoulder, elbow, and wrist). So, they decided to use high-speed videography and three-dimensional motion tracking to monitor, with exacting precision, the temporal landscape of twitch activity (Figure 1A).

By carefully analysing limb movements on a second to millisecond timescale, they immediately observed a clear temporal organization of forelimb twitches. They found that twitches of the shoulder, elbow and wrist were highly synchronized, with twitches in each of these limb structures occurring in very close temporal proximity to one another (Figure 1B). Moreover, when they looked at joint movements on a finer timescale (milliseconds) they noticed something truly remarkable. They found that twitches appear to be

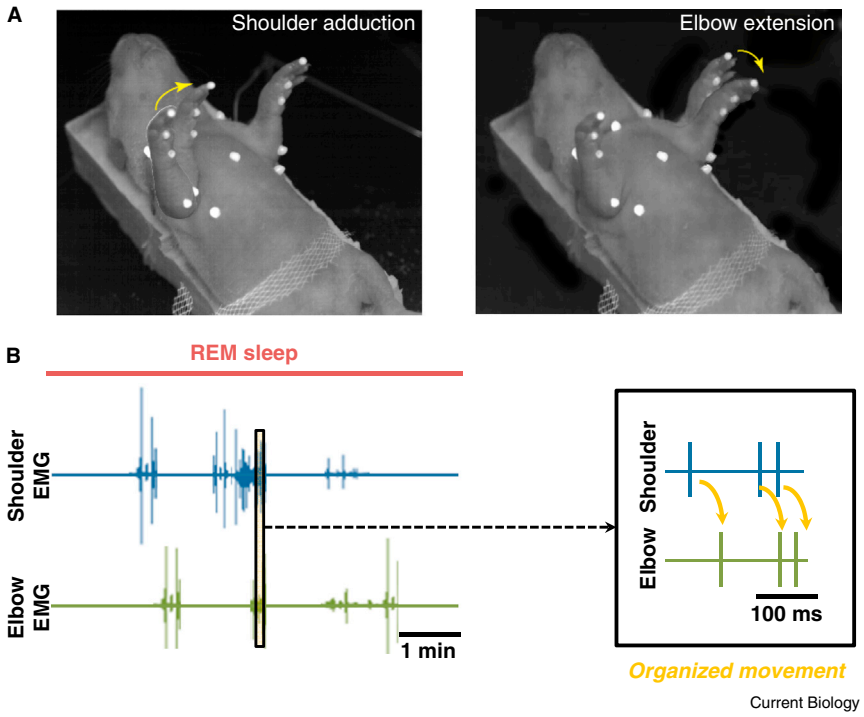

Figure 1. REM sleep twitches follow a well-organized pattern of movement.

(A) Example of time-lapse photographs, compiled from two high-speed video frames, of a supine eight-day-old rat exhibiting a discrete movement of the shoulder (adduction) and elbow (extension). The white dots were used for motion tracking of joint movements. Yellow arrows indicate direction of movement. (Adapted from [6].) (B) A schematic representation of how electromyographic (EMG) activity of the shoulder (blue) and elbow (green) of the same forelimb are spatiotemporally organized during REM sleep. Insert shows how, at a finer time-scale, shoulder and elbow joints clearly move in an organized manner, creating a purposeful movement. Each tick mark represents a muscle twitch at the shoulder and elbow. Yellow arrow indicates how these joints are synchronized (elbow following shoulder).

driving purposeful forelimb movements, as if the rats were reaching out to grab or touch something in space. They also found an apparent coordination between movements of the left and right forelimbs. Specifically, they showed that twitches in the left shoulder occur in remarkably close temporal proximity to those in the right shoulder, making it appear as if left and right limbs were mimicking each other's behaviours. Together, these findings demonstrate that REM sleep movements are not random in nature, but are instead highly structured, and organized into seemingly purposeful patterns of activity.

Not only did Blumberg *et al.* [6] find that REM sleep twitches drive coordinated limb movements, they also identified a developmental shift in both the pattern and fluidity of twitch-driven movements. They did this by documenting the organization and frequency of REM sleep movements in two-day-old rat pups and compared them with those expressed in eight-day-old pups. They made two fundamental observations, both of which suggest that twitch activity is influenced by development. First, they found that the most commonly executed limb movements in two-day-old pups became more refined in eight-day-old pups. Overall, they observed a marked increase in the accuracy and fluidity of movement in older animals, suggesting that over time more prevalent movement patterns are refined and less refined movements are eliminated. Second, they showed that the more refined and defined a particular movement pattern was in young animals, the more it was expressed and repeated in older animals, providing evidence of a selectionist process whereby movement patterns at early ages compete for retention and expression at older ages.

These findings provide direct evidence that sleep-driven muscle twitches are biologically purposeful. Going against the grain [4,5], Blumberg *et al.* [6] suggest that REM sleep

twitches are not biological accidents resulting from the brain's failure to maintain normal levels of muscle paralysis. Instead, they propose that muscle twitches and the resulting limb movements are deliberately triggered biological events that exhibit highly structured spatiotemporal patterns of activity [6]. Further supporting their hypothesis is their seminal observation that twitch-driven movements are under tight developmental control, with muscle movements becoming increasingly defined and refined with age.

Blumberg *et al.* [6] propose that the structurally organized pattern of REM sleep movements has important implications for understanding how brain and spinal mechanisms trigger twitches during sleep [3,9], an area of research that remains largely unexplored. They also suggest that sensory feedback from sleep-driven twitches play a critical role in the development of sensorimotor systems [9]. This suggestion fits nicely with their previous work, also published in *Current Biology* [12], showing that tactile feedback from whisker twitches triggers marked activation of corticothalamic circuitry *specifically during REM sleep* (but not during wakefulness). Sensory feedback during sleep may be more effective in driving sensorimotor organization [12] because externally generated motor signals are minimal or absent during REM sleep, and twitches clearly punctuate the noiseless background of muscle paralysis [13,14]. Lastly, Blumberg *et al.* [6] propose that twitches represent a previously unrecognized form of motor exploration that may lay the foundation for automatic and goal-directed movements during wakefulness [6].

But, this study [6] also raises a multitude of pressing questions. For example, it remains to be seen how (or if) the developing motor cortex uses and integrates sensory feedback produced by sleep movements. Do hindlimbs and other motor systems, such as respiratory [15] or oro-facial muscles [3,14], also act out a well-defined pattern of activity during REM sleep? And, does a coordinated muscular plan of action during REM sleep also persist into adulthood? Answering this last question could be of great value to understanding the pathophysiology of REM sleep behaviour disorder, a disease that afflicts older adults and results in excessive and often violent movements during REM sleep [16,17]. Determining the brain mechanisms that trigger sleep movements in developing animals could potentially be used to identify the circuits that breakdown and cause REM sleep behaviour disorder [16].

In summary, this new study [6] provides a fundamentally new framework for understanding motor control and function during REM sleep. Blumberg *et al.* [6] nicely show that REM sleep deliberately triggers twitches in forelimb muscles in infant rats, and that this activity is under strict and lawful control of the developing brain. Why the central nervous system triggers coordinated patterns of movement during sleep, and what the sleeping brain does with the tactile feedback from these events remain a mystery. But, determining how sleep-driven movements impact the developing brain will surely provide valuable clues into the functions of REM sleep.

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[1]Department of Cell & Systems Biology, [2]Department of Physiology, University of Toronto, Toronto, Ontario, M5S 3G5, Canada.
*E-mail: john.peever@utoronto.ca

http://dx.doi.org/10.1016/j.cub.2013.09.009

Cilium Assembly: Delivery of Tubulin by Kinesin-2-Powered Trains

The kinesin-2-driven anterograde transport of intraflagellar transport (IFT) trains has long been suspected to deliver cargo consisting of tubulin subunits for assembly at the axoneme tip. Important new work identifies the tubulin binding site on IFT trains that is responsible for this cargo transport.

Jonathan M. Scholey

Cilia are microtubule-based structures surrounded by a specialized membrane plus associated signaling molecules which project from the surface of virtually all eukaryotic cells and play key roles in cell motility and cilium-based signaling [1]. Cilium assembly [2] is known to depend upon